Fracture Strength of Fused Silica from Photonic Signatures around Collision Sites

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Outline

1. Background
2. Photoelasticity and Collision Dynamics
3. Fracture Strength and Photoelastic retardation: a power law function
   - Data for three classes of damage
   - Calculations from measurements
   - Possible effects of residual stress on material life
4. Conclusions & Future Directions

Background-Space Applications of Glass

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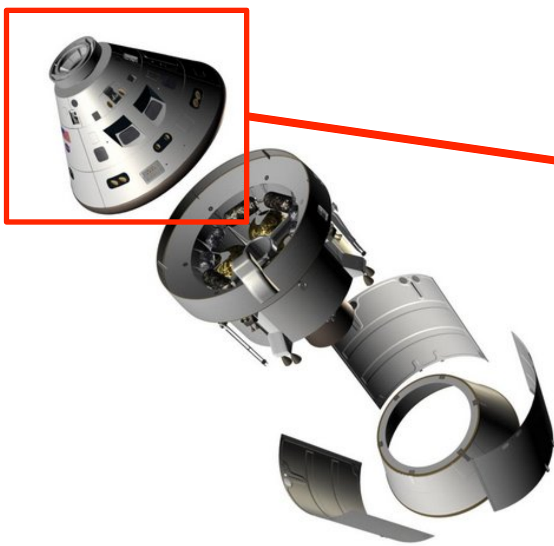
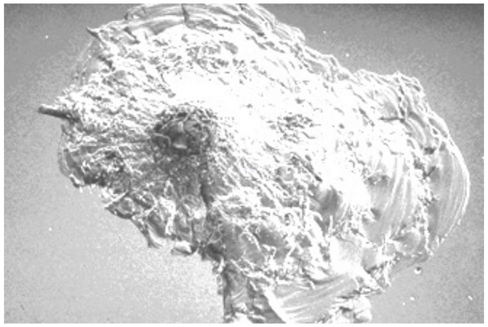
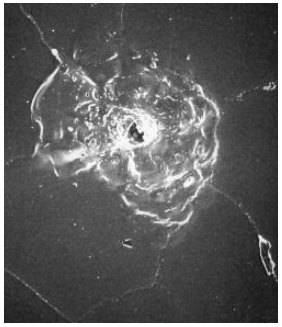


Background-Damage Incurred During Service Life



STS-35



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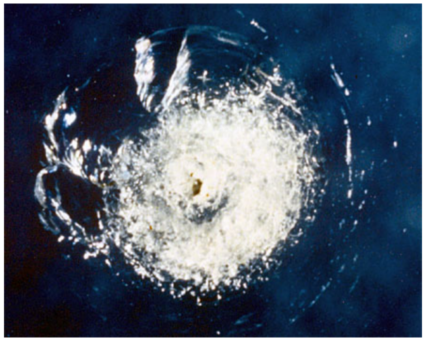


STS-7

Damage from high velocity impacts (HVI)

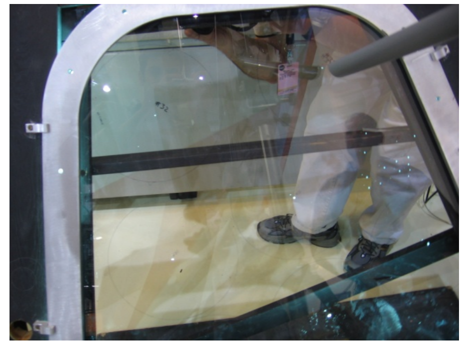
- Fused Silica is the material of choice
  - Tough
  - Good Optical and Thermal Properties
- Damage
  - Maintenance -> (Bruises)
  - Installation -> (Chatter Checks)
  - Orbit – (~11 Km/s) -> (HVI)

    impacts due to micromeoters

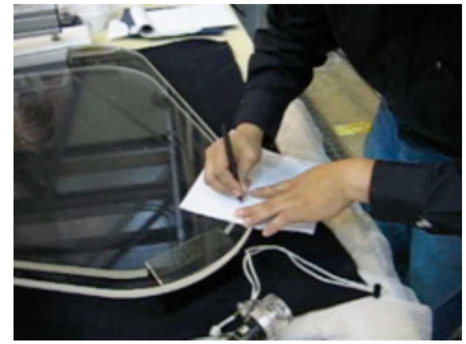
affects its mechanical strength

Fused Silica Study

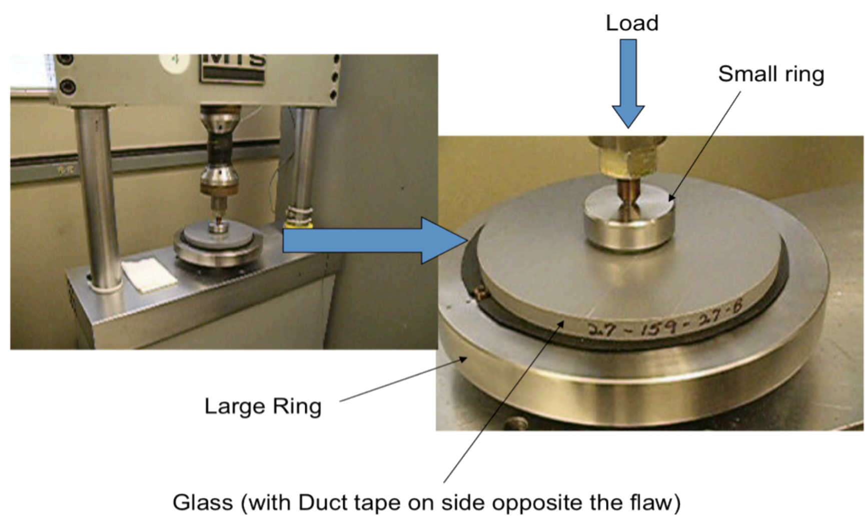
- Three Types of Damage
  - *HVI* , hyper velocity impacts encountered during shuttle flight
  - *Bruises,* impacts from low-velocity masses
  - *Chatter-checks*, sequential, inflicted with stylus (ball pen)
- Ring-on-Ring Breakage Strength Testing (SwRI)



Set-up for Bruises



Set-up for Chatter-Checks



Analysis of *collision dynamics* show a power-law relationship between collision energy and fracture strength.

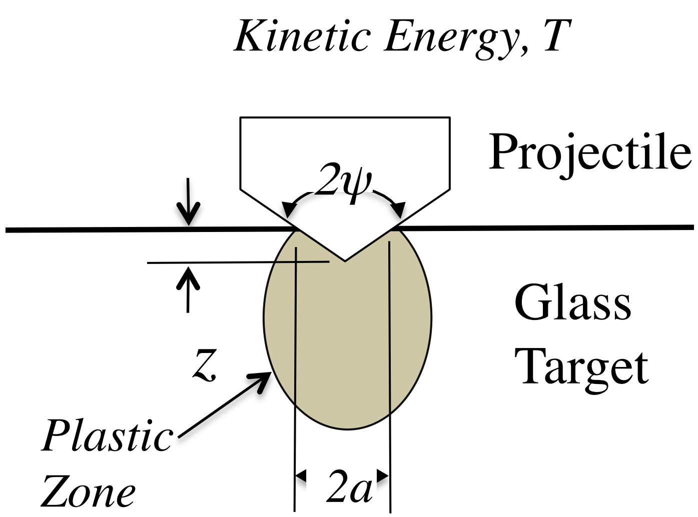
Photoelasticity, measured with a grey-field polariscope, is sensitive to residual stresses in glass, inflicted during the collision processes.

A functional relationship relates the residual stress surrounding the damage sites , shown by photoelastic retardation $\boldsymbol{R}$, and the deposited collision energy, $\boldsymbol{T}$. Hence we hypothesize that $\boldsymbol{R}$ should predict Fracture Strength, σ.

Images from the grey field polariscope are analyzed for photoelastic retardation and averaged over a circular path around the damage site.

2. PHOTOELASTICITY AND COLLISION DYNAMICS

Model Prediction from Collision Dynamics Analysis



$$\sigma_{fracture} = f(K_c, \hat{p}, \psi, H)T^{-2/9-\zeta} \quad *$$

where
H is hardness
p is mean stress
K_c is fracture toughness
ζ is a parameter that depends on damage class

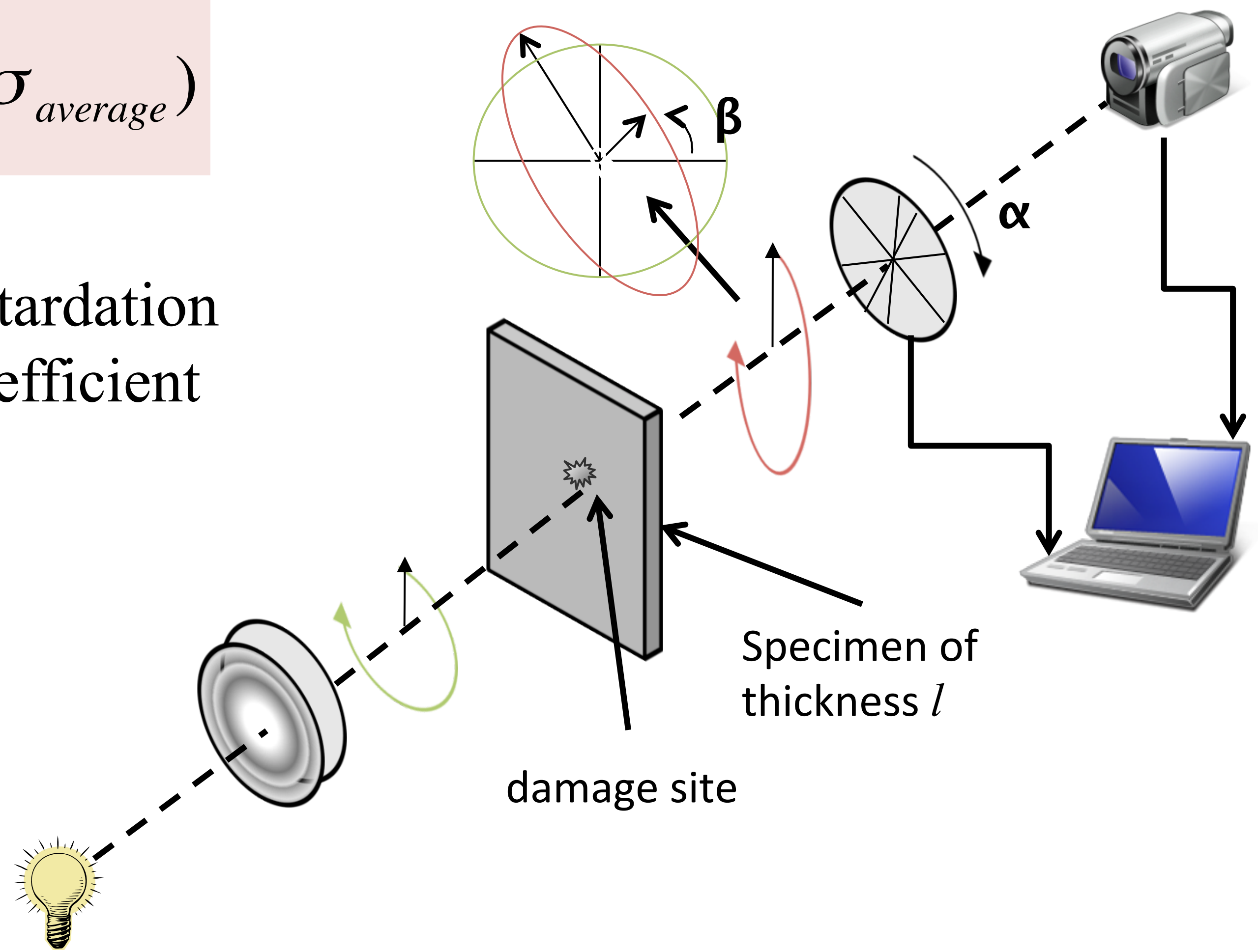
A Residual Stress zone in the glass surrounds the collision site

*W.T. Yost, K.E. Cramer, L.R. Estes, J.A. Salem, J. Lankford, Jr. and J. Lesniak, "Examination of Relationship between Photonic Signatures and Fracture Strength of Fused Silica Used in Orbiter Windows," NASA TP-2011-217322 (2011).

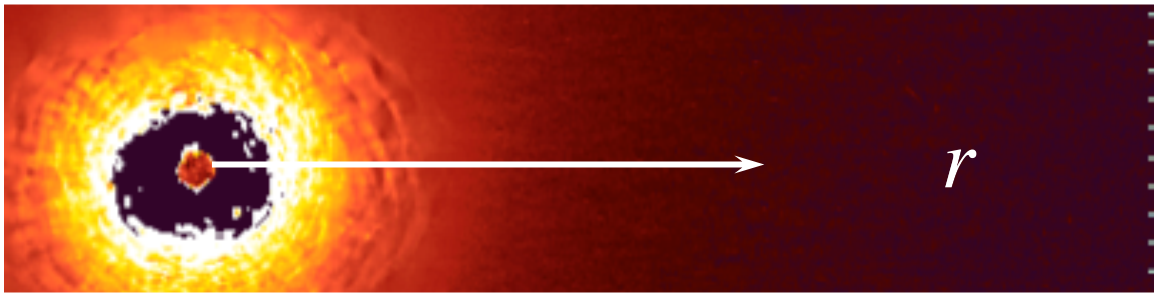
Stress Imaging in the Elastic Zone in Glass with Grey Field Polariscope

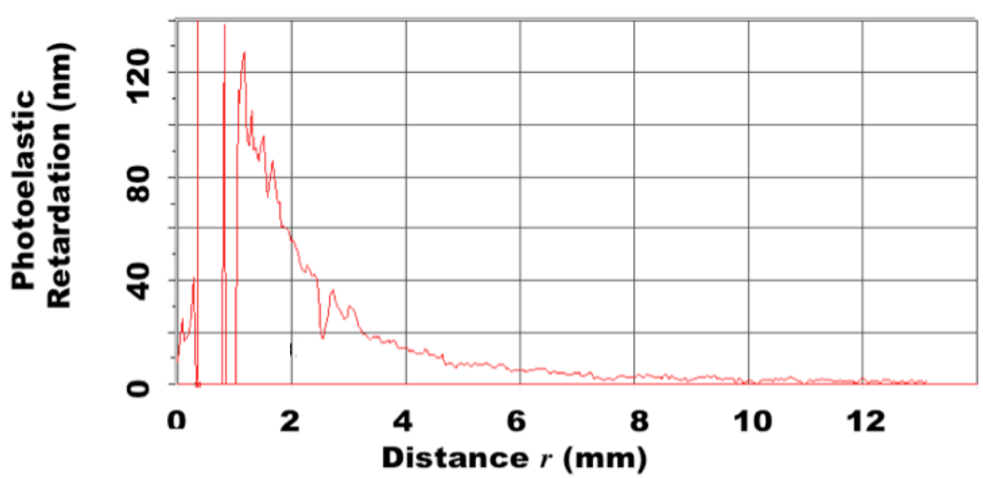
$$R_{average} = \frac{2\pi l K}{\lambda}(\sigma_{average})$$

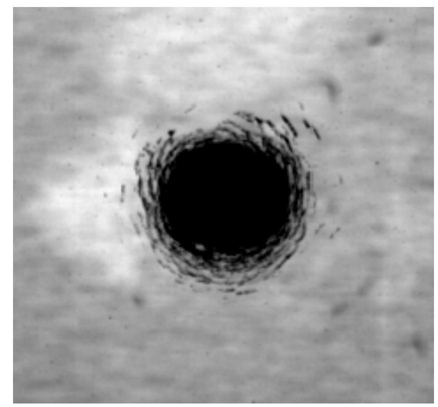
where
R is photoelastic retardation
K is stress-optic coefficient
λ is wavelength
l is glass thickness
σ is stress level



Photoelastic Retardation vs. Radius from Center of Impact





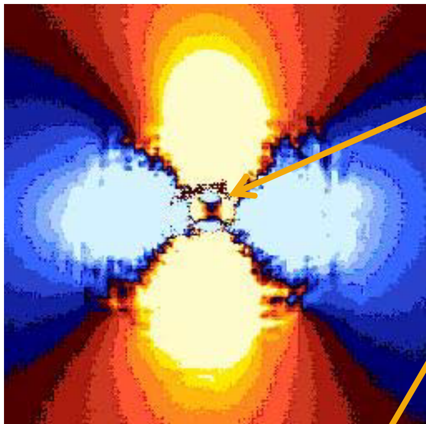


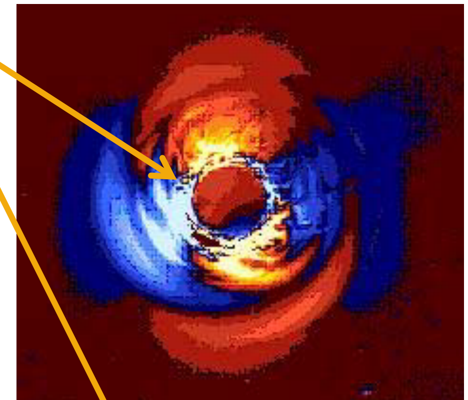
Optical Image of Damage Site

*W.T. Yost, K.E. Cramer, L.R. Estes, J.A. Salem, J. Lankford, Jr. and J. Lesniak, "Examination of Relationship between Photonic Signatures and Fracture Strength of Fused Silica Used in Orbiter Windows," NASA TP-2011-217322 (2011).

Typical Images

Different Magnifications

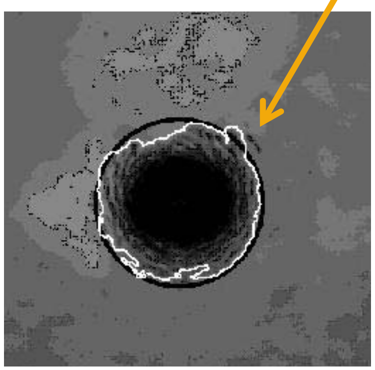


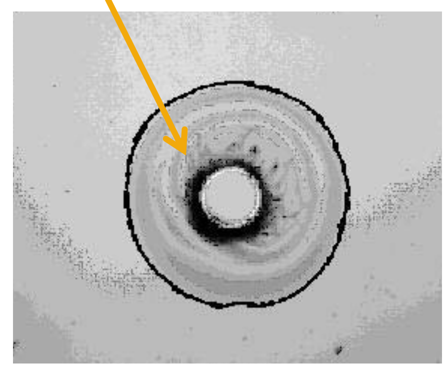


Grey Field Polariscope Image

Area outside visible damage zone averaged for characterization*

Visible Image





HVI ← *Damage Class* → Bruise

Three damage classes are considered here

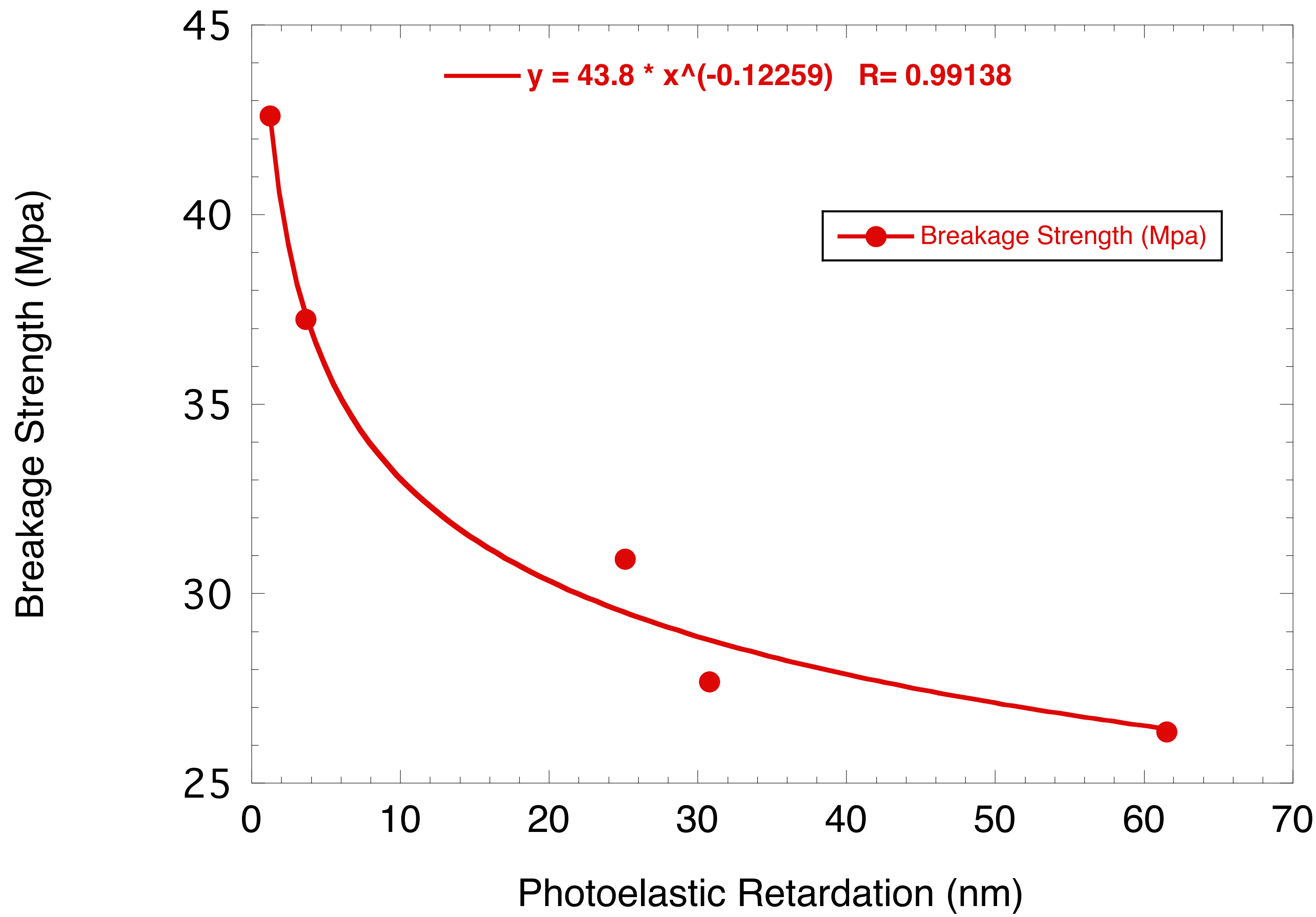
1. High velocity impacts
2. Bruises
3. Chatter-checks

Power-law relationships between fracture strength and photoelastic retardation appears to be consistent within each of the three damage classes.

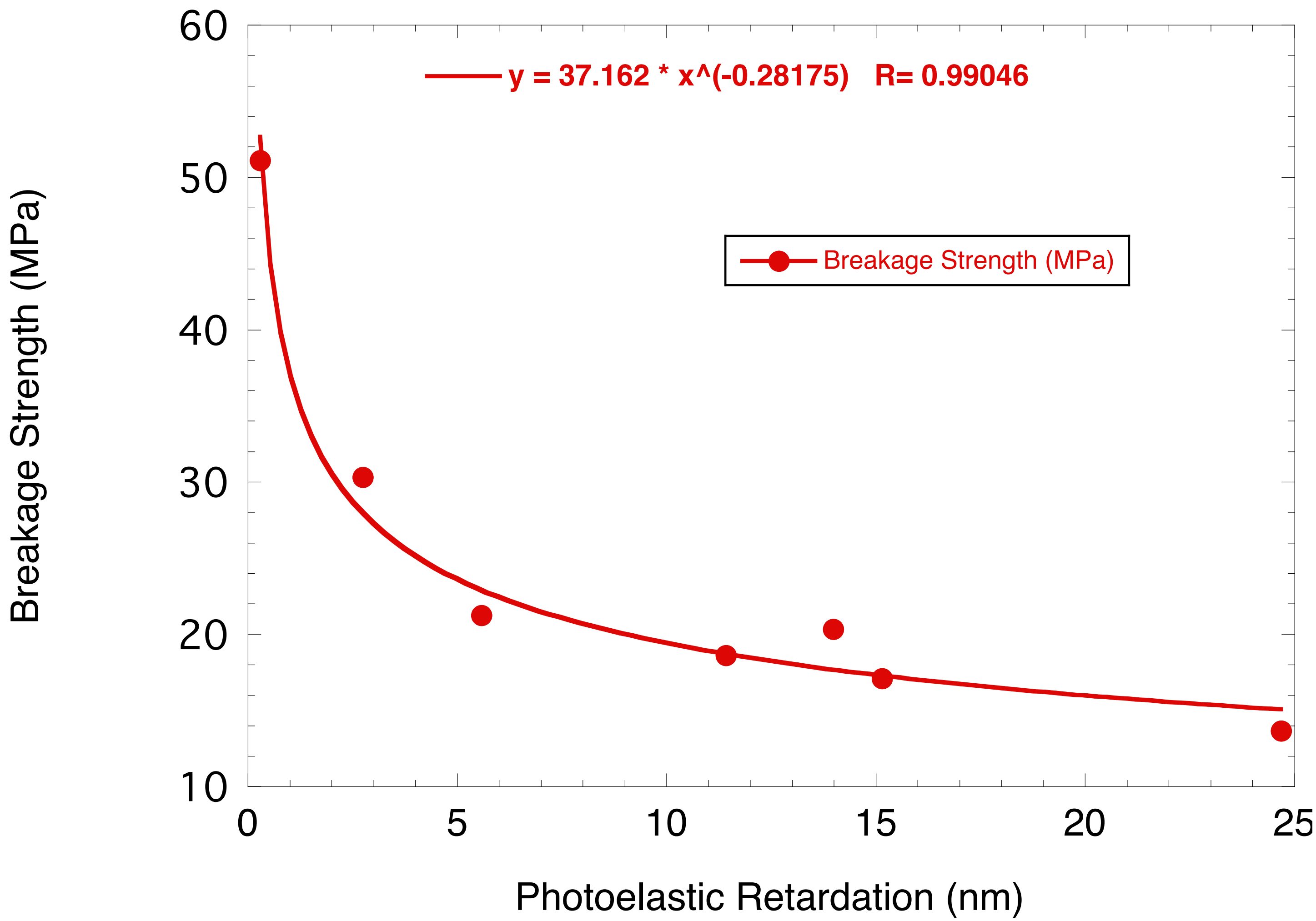
An R value below which Breakage stress is unaffected may exist

3. FRACTURE STRENGTH AND PHOTOELASTIC RETARDATION: A POWER LAW FUNCTION

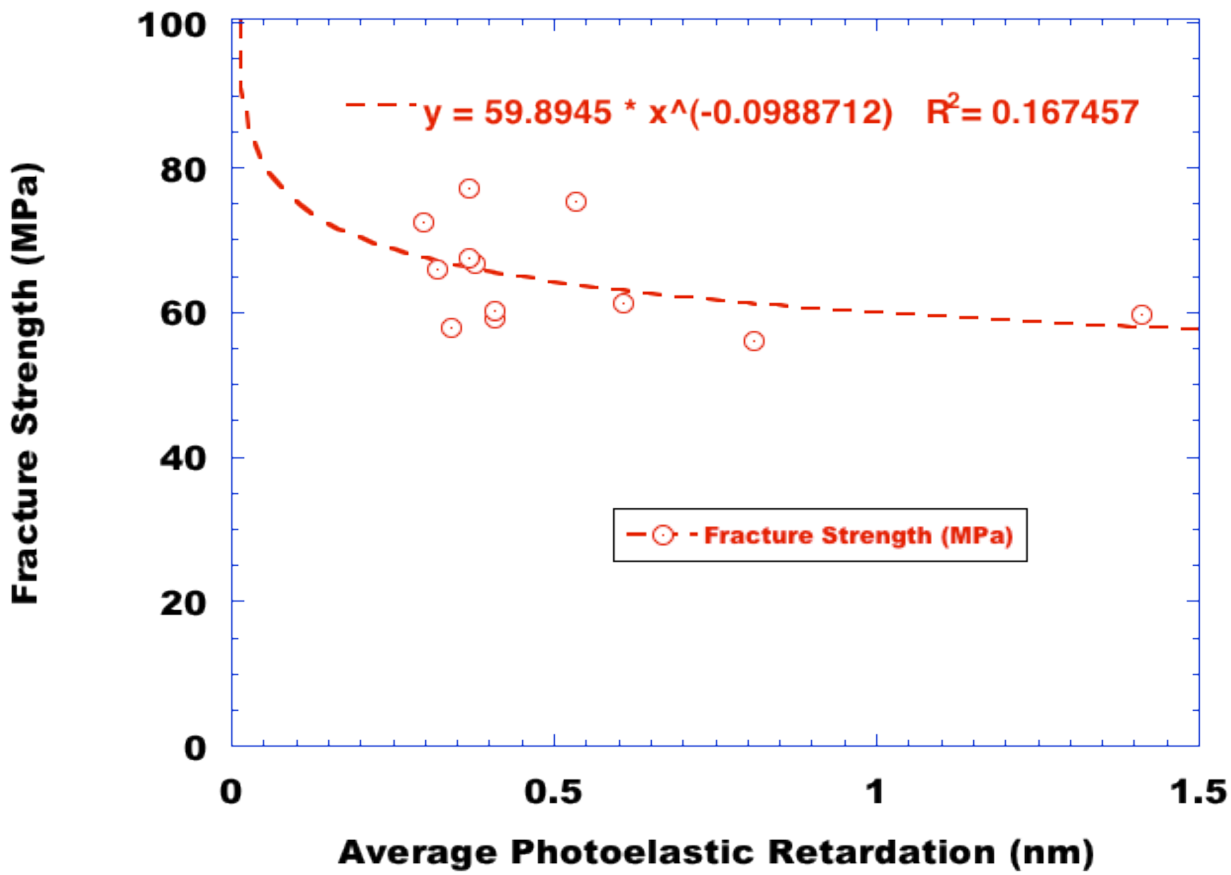
Results from High Velocity Impacts



Results from Bruising (Low Velocity) Impacts



Results from “Chatter Checks”



Calculations from Measurements

1. Maximum Photoelastic Retardation (R) for Minimal Effect on Breakage Strength

	HVI	Bruise	Chatter Check
R_{min} (nm)	0.456	0.323	0.61

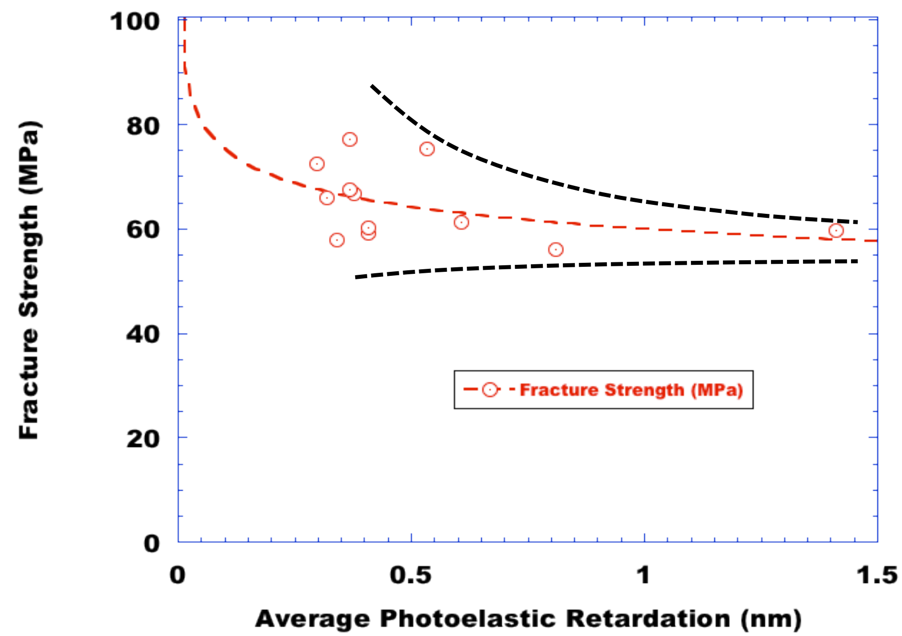
2. Power-Law for each damage type

$\sigma_{\max} = Ax^B$	HVI	Bruise	Chatter Check*
A	43.8	37.2	--
B	-0.1226	-0.2818	--

(data scatter too high for confidence)*

Effects of Residual Stress on Service Life

- Basis of derivation is that “flaws” within glass become unstable in presence of sufficient residual stress.
- Photoelastic retardation of chatter check damage may illustrate onset of flaw instability. Over time, this may affect breakage strength



Stress Calibration of this material shows residual stresses greater than 0.2 Mpa <u>may</u> lead to unstable “flaws”.

Discussion outlines the characteristics of data from HVI, Bruise, and Chatter-check specimens

Future work includes a measured stress-optic coefficient in acrylic, and poses a means to explore remaining life issues concerning "self-healing" polymers

4. DISCUSSION, CONCLUSIONS, AND FUTURE WORK

Discussion

- The average of the photoelastic retardation around the damage site correlates well with breakage stress for each class of damage
  - Visible damage is easily defined
  - Damage sizes were consistent across different specimens
- Greater scatter in the “chatter-check” data doesn’t correlate as well with breakage stress.
  - Visible damage region is much less localized (long and narrow in form)
  - Damage sizes (lengths) varied significantly
  - Photoelastic retardation near the detection limits of the system
- Chatter check and other data may show a basic premise about the power-law analysis - that “flaws” in glass are the progenitors of damage sites.
  - Below a certain level of R, the breakage strength is largely random within a region of breakage strengths
  - Above this level, the breakage appears to approach levels predicted by the value of R

Conclusions

- Photoelastic stress imaging shows promise in predicting fused silica breakage stress.
- A Power-law relating breakage stress in glass with is established for fused silica in three damage classes (HVI, Bruises, Chatter Checks)

Future Directions
Monitor Dynamics of Self-healing Thermoplastic Polymers

- Polybutadiene graft (PBg) copolymer
- Commercially available thermoplastic polymer that self-heal after ballistic impact and through-penetration.
- $K = 3.23 \pm 0.73 \times 10^{-12}$ pa^{-1}
- Is the residual stress related to the remaining strength of the specimen?